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Survey of Radiometric Calibration Results and Methods for Visible and Near Infrared Channels of NOAA-7, -9, and -11 AVHRRs

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Radiometric calibration methods for NOAA AVHRR reflectance channels are reviewed and calibration results for the NOAA-7, -9, and -11 AVHRRs are summarized. Expressions are provided for the gain values and calibration coefficients of these sensors. Analysis shows that significant errors may results in vegetation index calculations from use of prelaunch calibration values for NOAA-11 AVHRR. The postlaunch calibration methods are briefly discussed.

INTRODUCTION

Postlaunch radiometric calibration of the NOAA AVHRR solar reflection channels is of significant concern for the data users. No on-board calibration devices are available for these channels. The values and degradations in the instrument gain values have been checked by various methods. Research on the calibration methodology has been carefully evaluated, and the methods have been summarized in a special NOAA workshop report (NOAA, 1990).

Generally the methods can be grouped into three categories. The first is direct calibration by observing a desert area, the White Sands Missile Range (WSMR), from a high-altitude aircraft carrying a radiometer during the satellite overpass, as described by Smith et al. (1988), Abel et al. (1988), and Guenther et al. (1990). The second category is mainly based on radiative transfer models, target models, and image processing, with ground, cloud, or atmospheric phenomena as the calibration targets. Some atmospheric parameters have been measured for atmospheric correction, as described by Teillet et al. (1990). The methods of Justus (1989), Frouin and Gautier (1987), Kaufman et al. (1991), Slater et al. (1987), and Gu et al. (1991) fall in this category. The third category provides an estimation of sensor degradation rather than absolute calibration. This procedure uses long-term monitoring of one or more uniform desert areas to provide an average monthly or daily decrease of sensor gain. This last category includes the methods described by Kaufman and Holben (1991), Holben et al. (1990), Staylor (1990), and Brest and Rossow (1991), who use a large number of targets from a variety of land surfaces.

Radiometric calibration of NOAA-9 Channels 1 and 2 was addressed by the FIRE / SRB Cirrus and Marine Stratocumulus Intensive Field Operation, in October 1986 and July 1987 at WSMR (Whitlock et al., 1990). Numerous approaches were independently utilized in the data processing for intercomparison of different methods. As no method is generally agreed upon for post-

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launch radiometric calibration, calibration equations were recommended as a result of regression analysis of all available values.

Because of limitations of measurement accuracy and the complexity in modeling and data correction, the gain values in the literature show considerable scatter, which compromises the value of AVHRR data for studies of global change. Research is continuing in order to improve this state of affairs.

This paper analyzes the radiometric calibration and gain values for NOAA-7, -9, and -11 based on a summary of the calibration results by a number of scientists. Recommended equations for gain values and calibration coefficients are provided. Since errors in Normalized Difference Vegetation Index (NDVI) are directly related to the accuracy of the calibration, the effects of calibration errors on this quantity are presented. The final section summarizes the contribution of this paper.

SUMMARY OF GAIN VALUES FOR NOAA-11

Most results for AVHRR calibration have been presented in terms of instrument gain, where gain is defined as digital counts per radiance at the entrance pupil of the sensor. Thus, gain is the reciprocal of the calibration coefficient α, where radiance equals α (digital count) + β. We note that when instrument gain (sensitivity) decreases, the corresponding value of α increases.

A single gain value is appropriate here, applied over the radiometric dynamic range of the satellite sensor. The system is linear according to the physics of the detector and electronics, and linearity was empirically established at ITT, which built the instruments.

The gain values acquired by five different methods for the NOAA-11 AVHRR are listed in Table 1 and illustrated in Figure 1. (If the gain values reported by the authors are for a year, the data points are only marked in July of that year. The same applies for NOAA-7 and -9, as described later.) Each value can represent an average from several data points and has some uncertainty. In the table, Che et al. (1991) used one method with two different SPOT calibration coefficients as supplied by Optical Sciences Center (OSC) at the University of Arizona and by CNES, France.

For NOAA-11 AVHRR Channel 1, the gain values resulting from the different methods are relatively consistent. The data points from Justus appear abnormal: an increase of 7% about 3 months after November 1988 and a decrease of

Table 1. Gain Values of NOAA-11 AVHRR, Channels 1 and 2

	Methods	*Nov. 1988*	*Jan. 1989*	*Apr. 1989*	*May 1989*	*1989*	*Sep. 1989*	*1990*	*Jun. 1990*	*Oct. 1990*	*Mar. 1991*	*Degradation Rate/Year*
1	Abel (1991)[a]									1.77		
	Abel (1991)[b]	1.89		1.79		1.72		1.65	1.76	1.75		
	Justus (1989)[c]	1.91	2.04		1.82							8.1%
	Gu (1991)						1.78					
	Che (OSC) (1991)	1.80							1.69			3.8%
	Che (CNES) (1991)	1.82							1.78			1.4%
	Grant (1989)	1.79										
	Kaufman (1991) (desert)[d]					1.67		1.64			1.70	
2	Abel (1991)[a]									2.66		
	Abel (1991)[b]	2.94		2.82		2.68		2.53	2.69	2.78		
	Justus (1989)[c]	2.92	2.86		2.74							12.3%
	Gu (1991)						2.26					
	Che (OSC) (1991)	2.48							2.17			8.3%
	Che (CNES) (1991)	2.75							2.36			9.5%
	Grant (1991)	2.37										
	Kaufman (1991) (desert)[d]					2.57		2.50			2.50	1.6%

[a] Using Justus method.
[b] Abel, P. (1991), personal communication.
[c] The mean months of a period of 1–4 months.
[d] Holben, B. N. (1991), personal communication.

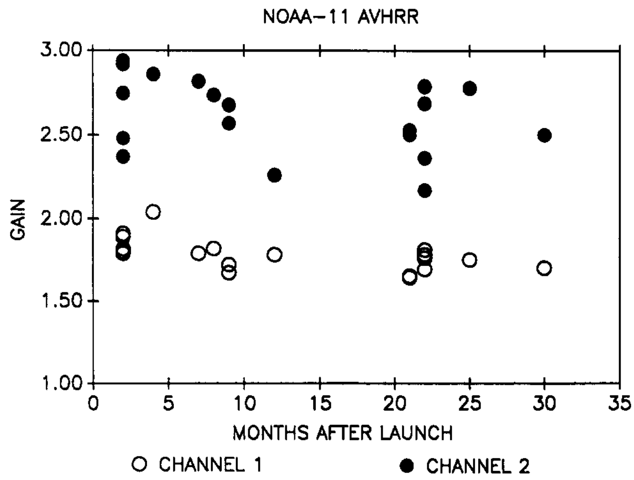

Figure 1. Gain values of NOAA-11 AVHRR.

11% in the subsequent four months. Excluding the abnormal cases, all 18 values fall in the range 1.78 ± 0.14.

The gain values for Channel 2 are scattered over a slightly larger range. The values can be divided into two groups. One set comes from the Abel and Justus methods and the other from Kaufman, Slater, and Gu's methods. The gain values in the first group are higher, with an average of 2.77. In the second group, the average gain value is 2.44, 12% lower than the first group.

COMPARISON OF GAIN VALUES FOR THE NOAA-7, -9, AND -11

The three AVHRRs for NOAA-7, -9, and -11 were manufactured as a group with different duration of storage prior to operation in orbit. For comparison of the performance of the three satellite sensors, the gain values and reference sources for the NOAA-7 and NOAA-9 AVHRRs are summarized in Tables 2 and 3. Placing these gain values in a single coordinate system, with launch dates set at the origin, we illustrate Channel 1 results in Figure 2 and Channel 2 results in Figure 3.

Several points are worth noting:

1. The prelaunch gain values in Channels 1 and 2 are 1.88 and 2.88 (calibration coefficient $\alpha = 0.532$, 0.347) for NOAA-7; 1.95 and 2.86 ($\alpha = 0.513$, 0.350) for NOAA-9 (Price, 1988); and 2.04 and 3.32 ($\alpha = 0.490$, 0.301) for NOAA-11 (Abel, 1990). The coefficients for NOAA-11 were revised in April 89 by ITT (Abel, 1990).

The differing degradation rates for Channels 1 and 2 lead to time varying errors in the calculation of NDVI, when the prelaunch gain values are used in postlaunch data processing (discussed in the fourth section).

2. The gain values from different methods fall in a narrow band for Channel 1. An equation for gain can be established by linear regression. For NOAA-9, the equation is

$$\text{gain} = 1.763 - 6.860 \times 10^{-3} \times \text{months} \quad \text{counts}/(\text{W m}^{-2}\ \text{sr}^{-1}\ \mu\text{m}^{-1}), \tag{1}$$

where months are counted from the launch date (here and in the following). For NOAA-11, the result is

$$\text{gain} = 1.859 - 5.990 \times 10^{-3} \times \text{months} \quad \text{counts}/(\text{W m}^{-2}\ \text{sr}^{-1}\ \mu\text{m}^{-1}). \tag{2}$$

We observe that gain changes for the two satellite sensors are nearly the same. Without compromising accuracy, an average gain degradation rate for the two sensors is given by

Table 2. Gain Values of NOAA-7 AVHRR, Channels 1 and 2

	Year	*1981*	*1982*	*1983*	*Aug. 1983*	*Nov. 1983*	*1984*	*Degradation Rate / Year*
1	Justus (1989)				1.75			
	Frouin (1987)[a]					1.57		
	Kaufman (1991) (desert)	1.61	1.54	1.49			1.45	3.5%
	Kaufman (1991) (ocean)	1.52	1.56	1.61			1.61	−6.6%
	Staylor (1990)							3.5%
2	Justus (1989)				2.48			
	Frouin (1987)[a]					2.41		
	Kaufman (1991) (desert)	2.44	2.27	2.17			2.13	4.2%
	Kaufman (1991) (ocean)	2.17	2.27	2.33			2.44	−12.4%

[a] The original data are 0.0681 and 0.1007 (W m^{-2} sr^{-1} / count) for Channels 1 and 2, respectively. Here the bandwidth, 0.107 μm and 0.243 μm, are taken into account for consistency of units.

Table 3. Gain Values of NOAA-9 AVHRR, Channels 1 and 2

	Year	1985	Aug. 1985	1986	Oct. 1986	Nov. 1986	May 1987	1987	Feb. 1988	1988	Nov. 1988	Degradation Rate/Year
1	Justus (1989)									1.58		
	Kaufman (1991) (desert)	1.67		1.59				1.47		1.41		5.2%
	Kaufman (1991) (ocean)	1.59		1.59				1.45				4.4%
	Brest (1991)		1.77		1.68		1.64		1.59		1.53	4.1%
	Teillet (1990)		1.83		1.37		1.50		1.40			10.1%
	Whitlock (1990) (cirrus)				1.65							
	Whitlock (1990) (marine)							1.58				
	NOAA aircraft[a]		1.92			1.67			1.53			9.0%
	Frouin (1987)	1.72		1.61								4.0%
2	Justus (1989)									2.58		
	Kaufman (1991) (desert)	2.38		2.33				2.22		2.17		2.9%
	Kaufman (1991) (ocean)	2.27		2.27				2.27				0%
	Teillet (1990)		2.57		2.06		2.28		2.16			6.8%
	Whitlock (1990) (cirrus)				2.50							
	Whitlock (1990) (marine)							2.41				
	NOAA aircraft[a]		2.78			2.50			2.35			6.6%
	Frouin (1987)	2.70		2.56								5.2%

[a] Data is from Teillet (1991).

$$\text{gain} = A - 6.425 \times 10^{-3} \times \text{months}$$
$$\text{counts}/(\text{W m}^{-2}\ \text{sr}^{-1}\ \mu\text{m}^{-1}), \qquad (3)$$

where the coefficients A listed in Table 4 were obtained after fixing the degradation rate of 6.425×10^{-3} for both sensors. The value of A corresponds to the sensor gain during initial operation in orbit.

The calibration of NOAA-7 has been estimated from a small number of data points. Different methods give a range of values. Kaufman's two methods yield opposite tendencies for calibration changes. However, Kaufman's result (using desert as the calibration target) agrees with Staylor's, yielding a rate of change for Channel 1 of 3.5% per year or 5.011×10^{-3} per month. The extreme

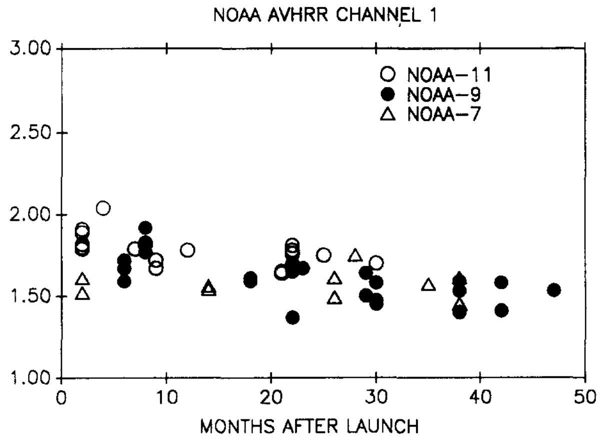

Figure 2. Gain values of NOAA-7, -9, -11 AVHRR channel 1.

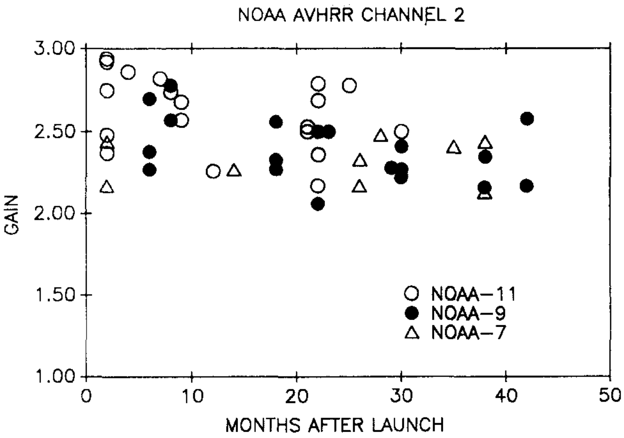

Figure 3. Gain values of NOAA-7, -9, -11 AVHRR channel 2.

Table 4. Formulas for Gain Values (count / W m^{-2} sr^{-1} μm^{-1})

Channel	Name of Sensor	Launch Date	Prelaunch Gain	Formulas for Gain
1	NOAA-7	23 Jun. 1981	1.88	$1.707 - 6.425 \times 10^{-3} \times$ months
	NOAA-9	12 Dec. 1984	1.95	$1.752 - 6.425 \times 10^{-3} \times$ months
	NOAA-11	24 Sep. 1988	2.04	$1.864 - 6.425 \times 10^{-3} \times$ months
2	NOAA-7	23 Jun. 1981	2.88	$2.411 - 2.167 \times 10^{-3} \times$ months
	NOAA-9	12 Dec. 1984	2.86	$2.411 - 2.167 \times 10^{-3} \times$ months
	NOAA-11	24 Sep. 1988	3.32	$2.725 - 8.250 \times 10^{-3} \times$ months

similarity in the Channel 1 degradation rates for the three sensors is apparent in Figure 2. We suggest that the degradation rate for NOAA-7 is the same as that for the other two sensors, and obtain the coefficient A for NOAA-7 by the same method as NOAA-9 and -11 (Table 4, column 5).

The difference between the coefficient A and the corresponding prelaunch values are 0.17, 0.20, and 0.18 for NOAA-7, -9, and -11, respectively. This indicates that an average change of 0.18, that is, a 10% decrease of the gain value, appears very soon after launch. This change of instrument sensitivity may occur during the long storage period and/or due to outgassing in the first days or weeks in orbit.

Gain values have been obtained by researchers in several ways. Some used a fixed offset for counts at zero radiance, generally 35–40 digital counts, obtained when the sensor scanning mirror was oriented toward deep space. Others used linear regression in terms of digital counts versus radiance, which yields offset values (Brest and Rossow, 1991). The offset is a dependent variable in this case. Most reported offset data has used the deep space measured values. Che et al. (1991) used the Lava Beds, located at the northern part of the WSMR with reflectance less than 0.1, to examine the offset. The result was that after atmospheric correction the offset agrees with the deep space measurement. Thus use of deep space measured data for the offset is recommended.

3. Examining the data points for Channel 2 (Fig. 3), we see that a common rule is difficult to obtain. The data points for NOAA-7 and -9 are scattered about a mean value, indicating no change or a slight degradation during a period of 4 years after launch. As the degradation rate and the prelaunch gain values are nearly the same for NOAA-7 and -9, the data have been combined to determine a common degradation rate of 1.1% per year, as indicated in Table 4.

Prediction of the degradation rate for NOAA-11 AVHRR is somewhat complicated. Abel et al. (1991, personal communication), using aircraft overflight measurements, indicate a degradation rate of 5% per year during the first 500 days in orbit and then a recovery rate of 10% per year in the next 200 days. Kaufman et al.'s desert method suggests only slight degradation occurred. However, Justus et al. and Slater et al. show a significant loss of instrument sensitivity. The differences between prelaunch gain and the corresponding coefficients A for the NOAA-7, -9, and -11 Channel 2 are 0.47, 0.45, and 0.60, representing a loss of sensitivity of about 20% for the period in storage and immediately after launch.

4. The gain values for Channel 2 have larger uncertainty than those for Channel 1, based upon the reported information. Che et al. (1991) noticed that greater uncertainty is produced for Channel 2 than Channel 1, assuming the same percentage errors in atmospheric correction factors. Using modeled instead of taking measured water vapor content can be an additional factor, mainly affecting AVHRR Channel 2. Kaufman and Holben (1991) used ocean glint phenomena to transfer the coefficient from Channel 1 to Channel 2. This causes an additional increase in uncertainty for Channel 2. The calibration accuracy claimed by various scientists is summarized in Table 6. The absolute accuracy is in the range of ±7–12%. Slater et al. (1987) add separate error items and attribute the main uncertainty to the previously mentioned SPOT HRV calibration uncertainty of ±6%. Considering atmospheric correction, image matching and variation in apparent radiance, the uncertainty is increased to ±7.5–10%, depending on the channel, as reported by Che et al. (1991). Kaufman and Holben (1991) state that aerosol optical thickness is the main contributor to the uncertainty in the atmospheric model calculation for Channel 1, causing ±10%

Table 5. Formulas for Calibration Coefficients ($W\ m^{-2}\ sr^{-1}\ \mu m^{-1}$ / count)

Channel	Sensors	Prelaunch Calib. Coeff.	Formulas
1	NOAA-7	0.532	$0.591 + 2.23 \times 10^{-3} \times$ months
	NOAA-9	0.513	$0.576 + 2.23 \times 10^{-3} \times$ months
	NOAA-11	0.490	$0.534 + 2.23 \times 10^{-3} \times$ months
2	NOAA-7	0.347	$0.420 + 2.33 \times 10^{-3} \times$ months
	NOAA-9	0.350	$0.420 + 2.33 \times 10^{-3} \times$ months
	NOAA-11	0.301	$0.369 + 1.20 \times 10^{-3} \times$ months

uncertainty. Transferring from Channel 1 to Channel 2 increases the uncertainty to $\pm 12\%$. Smith et al. (1987) analyzed the accuracy in detail. The main contributor to the absolute calibration uncertainty of $\pm 6\%$ arises from tracing the airborne instrument to the NIST standard. Instability in aircraft attitude control adds some uncertainty during the measurement, as it causes an error in ground location. The absolute calibration accuracy for the NOAA AVHRR is estimated at the level of $\pm 7\%$.

5. In order to facilitate use of the AVHRR for applications we provide calibration coefficients ($W\ m^{-2}\ sr^{-1}\ \mu m^{-1}$ / count) in Table 5, so that users may compute radiance from digital counts.

ERRORS IN THE CALCULATION OF VEGETATION INDICES BY USING PRELAUNCH GAIN VALUES

Perhaps the major use of AVHRR Channels 1 and 2 is for vegetation assessment (Tarpley et al., 1984; Tucker et al., 1985; Gallo and Flesch, 1989; Weinreb, 1991). For climate and agriculture applications, the Channel 1 and 2 reflectance values are used to compute the normalized difference vegetation index, given by

$$\mathrm{NDVI} = \frac{(\alpha_2 / S_2)(\mathrm{DC}_2 - \mathrm{OFF}_2) - (\alpha_1 / S_1)(\mathrm{DC}_1 - \mathrm{OFF}_1)}{(\alpha_2 / S_2)(\mathrm{DC}_2 - \mathrm{OFF}_2) + (\alpha_1 / S_1)(\mathrm{DC}_1 - \mathrm{OFF}_1)}, \tag{4}$$

Table 6. Estimated Calibration Accuracies

Methods	Absolute Accuracy Channel 1	Absolute Accuracy Channel 2
Che et al. (1991)	± 7.5%	± 10%
Kaufman et al. (1991)	± 10%	± 12%
Smith et al. (1988)	± 7%	

where α is the calibration coefficient in $W\ m^{-2}\ sr^{-1}\ \mu m^{-1}$/count, DC_1 and DC_2 are count values in Channels 1 and 2, and OFF_1 and OFF_2 are the corresponding offset counts. Here the calibration coefficient is defined by

$$\alpha = 1 / \mathrm{gain} \quad \text{(radiance/counts)},$$

and S is the value of the exoatmospheric solar irradiance, as needed to convert radiance to reflectance (Price, 1987). The formula for NDVI does does not include factors compensating for solar azimuth angles and viewing geometry or atmospheric absorption and scattering, but acquisition of sufficient data over time should provide a reliable indication of change in NDVI. In contrast, temporal variations of the AVHRR instruments and possible differences between instruments over the 13-year period of observations can disrupt efforts to understand the seasonal and annual changes of surface vegetation conditions. We may estimate the error introduced by using prelaunch gain values by taking the difference between NDVI calculated with prelaunch values and the result using values recommended here. Distinguishing prelaunch values from postlaunch values by adding primes, the absolute error in NDVI is expressed by

$$\Delta\mathrm{NDVI} = \mathrm{NDVI}' - \mathrm{NDVI} = \frac{1}{\gamma}\, \frac{(\gamma' - \gamma)(1 + \mathrm{NDVI})}{\gamma'(1 + \mathrm{NDVI}) / \gamma(1 - \mathrm{NDVI}) + 1} \tag{5}$$

where $\gamma = \alpha_2 / \alpha_1$ and $\gamma' = \alpha_2' / \alpha_1'$. In the approximation $\gamma' \approx \gamma$, we find

$$\Delta\mathrm{NDVI} = (1 / 2\gamma)(\gamma' - \gamma)(1 - \mathrm{NDVI}^2). \tag{6}$$

The maximum error in NDVI occurs when NDVI is zero and the minimum when $\mathrm{NDVI} = \pm 1$, as illustrated in Figure 4. Since NDVI generally falls in the range -0.1 to 0.6, the error may be regarded as linear with NDVI over this range (Kaufman and Holben, 1991). The

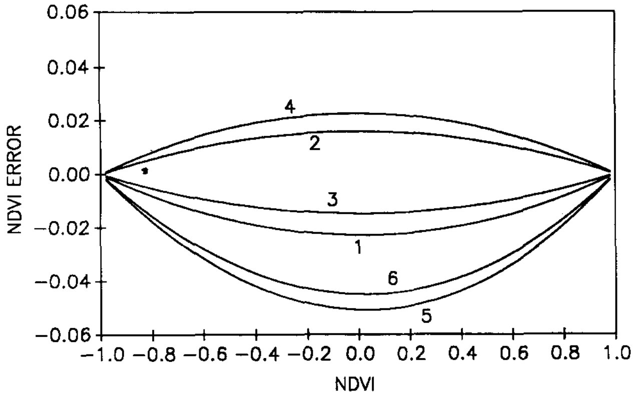

Figure 4. NDVI error as a function of NDVI: 1) NOAA-7 1.5 years after launch; 2) NOAA-7 3 years after launch; 3) NOAA-9 1.5 years after launch; 4) NOAA-9 3 years after launch; 5) NOAA-11 1.5 years after launch; 6) NOAA-11 3 years after launch.

influence of calibration errors may be expected to be small for both NOAA-7 and -9. However, in the case of NOAA-11, this effect is greater, yielding an error of 0.03, or about 5%, for dense vegetation with NDVI≈0.6, and greater error at smaller NDVI values. An ongoing calibration program is recommended for those using AVHRR to assess vegetation conditions.

DISCUSSION OF THE CALIBRATION METHODS

From a comprehensive survey of the radiometric calibration methods, the one most commonly adopted by the scientists is the use of a ground-based target as calibration site. Ideally the site should be a very large, flat, and horizontal area, uniform in reflectance, with no vegetation or cultural features. The reflectance should be high and stable with time, and the optical reflection characteristics should be as nearly lambertian as possible. In addition, the site should be in a region with mostly clear skies and good visibility. Deserts seem most appropriate to meet these requirements.

The Libyan Desert has been selected as a calibration site due to very stable atmospheric and ground conditions (Staylor, 1990). Other desert areas may also be used, such as the White Sands Missile Range in the United States (Slater et al., 1987; Frouin and Gautier, 1987). Although the White Sands uniform areas with high reflectance are not as large as the Libyan Desert, direct measurements of ground reflectance may readily be obtained over an AVHRR-sized area, offering the possibility of absolute calibration. Consistent monitoring of a given area together with the measurement of atmospheric parameters and meteorological data provides the variation rate of the gain over time. The fact that White Sands data may be processed for both absolute and relative calibration avoids the need to anchor relative calibration results obtained from one site to absolute calibration results derived at another site, with possible loss of accuracy.

Although each method has its accuracy limitation for satellite calibration, the potentially most accurate method may be the measurement of the radiance by a high-altitude aircraft over a high-reflectance region during the satellite overpass. Proper identification of the area measured by the aircraft and satellite is a key factor. The aircraft should fly with the same viewing angle as the satellite in order to reduce the effects of nonlambertian characteristics, relief of the ground, shadowing, and footprint difference, which are important error sources for acquisition of comparable apparent radiances (Che et al., 1991). A well-calibrated spectrometer or radiometer is needed with bandpass filters matching the satellite sensor's in order to minimize spectral reflectance variations across the sensor's bandwidth. Minimum differences in spectral response and in viewing and illumination conditions are prerequisites for accurate radiometric calibration using the approach. High-altitude observations make atmospheric correction simple because the optical thickness and water vapor absorption are common to both measurements, and only a small correction is needed for ozone and Rayleigh scattering above the aircraft.

Optical phenomena of the atmosphere are utilized by some scientists for radiometric calibration. Atmospheric scattering over the ocean is a large part of the total upwelling radiance. Molecular scattering can be calculated accurately, leaving the uncertainty in the radiance at the satellite altitude subject to error in the description of the atmosphere, in particular of the aerosol and water vapor content. Ocean targets yield greater uncertainty than the desert targets because the signal level is much lower. Although cloud top in uniform overcast conditions may also be used as a calibration target, models for the bidirectional reflectance function (BRF) of cloud must be improved. The difficulty lies in the consideration of cloud nonuniformity (Abel, 1991) and the accuracy of the BRF modeling. Conversion from the hemispheric exitance to the radiance in the sensor's viewing direction is the main challenge.

CONCLUDING REMARKS

Radiometric gain values and calibration coefficients for the NOAA-7, -9, and -11 AVHRR have been reviewed, and recommended values have been derived from the existing data. It appears that all three sensors behave in similar fashion, except that Channel 2 of NOAA-11 degrades at a different rate from NOAA-7 and NOAA-9. The calibration accuracy for the three satellite sensors is estimated to be at the level of $\pm 10\%$. It appears that the instruments are relatively stable, that is, change only slowly with time, and that accuracy of the gain values is more limited by our methods to determine them than by short term variability of the instruments. Evidence has been found for a loss of sensitivity during storage and initial period after satellite launch. Because of the significant errors associated with current postlaunch calibration techniques, we must consider the results presented here as subject to change or reevaluation when further research improves our understanding of this problem.

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REFERENCES

Abel, P. (1990), Prelaunch calibration of the NOAA-11 AVHRR visible and near IR channels, *Remote Sens. Environ.* 31:227–229.

Abel, P. (1991), Clouds as calibration targets for AVHRR reflected-solar channels: results from a two-year study at NOAA / NESDIS, *Proc. SPIE,* Vol. 1493.

Abel, P., Smith, G. R. Levin, R. H., and Jacobowitz, H. (1988), Results from aircraft measurements over White Sands, New Mexico, to calibrate the visible channels of spacecraft instruments, in *Proc. SPIE,* Vol. 924.

Brest, C. L., and Rossow, W. B. (1991), Radiometric calibration and monitoring of NOAA AVHRR data for ISCCP, *Int. J. Remote Sens.* 13:235–273.

Che, N., Grant, B. G., Flitter, D. E., et al. (1991), Results of calibrations of the NOAA-11 AVHRR made by reference to calibrated SPOT imagery at White Sands, New Mexico, *Proc. SPIE,* Vol. 1493.

Frouin, R., and Gautier, C. (1987), Calibration of NOAA-7 AVHRR, GOES-5 and GOES-6 VISSR / VAS solar channel, *Remote Sens. Environ.* 22:73–101.

Gallo, K. P., and Flesch, T. K. (1989), Large-area crop monitoring with the NOAA AVHRR: estimating silking stage of corn development, *Remote Sens. Environ.* 27:73–80.

Grant, B. G. (1991), Calibration of the Advanced Very High Resolution Radiometer, M. S. thesis, University of Arizona, 71 pp.

Gu, X. F., Verbrugghe, M., and Guyot, G. (1991), Interetalonnage de SPOT 1-HRV, LANDSTAT 5-TM et NOAA 11-AVHRR dans les domaines du visible et du proche infrarouge, in *Cinquième Coll. Int. Mesures Physiques et Signatures en Télédétection,* 14–18 January, Couchevel.

Guenther, B. W., Galimore, R., Markham, B. L., and Cooper, J. (1990), Result from the NASA ER-2 aircraft experiment at White Sands, N. M., Meeting on Radiometric Calibration of Satellite Sensors of Reflected Solar Radiation, NOAA NESDIS, 27–28 March.

Holben, B. N., Kaufman, Y. J., and Kendall, J. D. (1990), NOAA-11 AVHRR visible and near-IR inflight calibration, *Int. J. Remote Sens.* 11:1511–1519.

Justus, C. G. (1989), An operational procedure for calibrating and assessing the stability and accuracy of shortwave satellite sensors, Final Report to NOAA / NESDIS and USDA / ARC, 99 pp.

Kaufman, Y. J., and Holben, B. N. (1992), Calibration of the AVHRR visible and near-IR bands by atmospheric scattering, ocean glint, and desert reflection, *Int. J. Remote Sens.*, forthcoming.

NOAA (1990), Report of the Workshop on Radiometric Calibration of Satellite Sensors of Reflected Solar Radiation, NOAA Technical Report NESDIS 55, Washington, DC, 33 pp.

Price, J. C. (1987), Calibration of satellite radiometers and the comparison of vegetation indices, *Remote Sens. Environ.* 21:15–27.

Price, J. C. (1988), An update on visible and near infrared calibration of satellite instruments, *Remote Sens. Environ.* 24:419–422.

Slater, P. N., Biggar, S. F., Holm, R. G., et al. (1987), Reflectance based and radiance based methods for the inflight absolute calibration of multispectral sensors, *Remote Sens. Environ.* 22:11–37.

Smith, G. R., Levin, R. H., Abel, P., and Jacobowitz, H. (1987), Calibration of the solar bands of the NOAA-9 AVHRR and GOES-6 VISSR using high altitude aircraft measurements, presented at Int. Union of Geophysics, Vancouver, Canada.

Smith, G. R., Levin, R. H., Abel P., and Jacobowitz, H. (1988), Calibration of the solar bands of the NOAA-9 AVHRR using high altitude aircraft measurements, *J. Atmos. Ocean. Technol.* 5:631–639.

Staylor, W. F. (1990), Degradation rates of the AVHRR visible channel for the NOAA 6, 7, and 9 spacecraft, *J. Atmo. Ocean. Technol.* 7:411–423.

Tarplay, J. D., Schneider, S. R., and Money, R. L. (1984), Global vegetation indices from the NOAA-7 meteorological satellite, *J. Climate Appl. Meteorol.* 23:491–494.

Teillet, P. M., Slater, P. N., Mao, Y., et al. (1990), Three methods for the absolute calibration of the NOAA AVHRR sensors in flight, *Remote Sens. Environ.* 31:105–120.

Teillet, P. M. (Canada Centre for Remote Sensing) (1991), personnal communication.

Tucker, C. J., Townshend, J. R. G., and Goff, T. E. (1985), African land-cover classification using satellite data, *Science* 227:369–375.

Weinreb, M. P. (NOAA / NESDIS) (1991), personnal communication.

Whitlock, C. H., Staylor, W. F., Smith, G., et al. (1990), AVHRR and VISSR satellite instrument calibration results for both cirrus and marine stratocumulus IFO periods, NASA CP 3083.